# CO-OPERATIVE SPECTRUM SENSING IN COGNITIVE RADIO NETWORKS

Synopsis of the PhD Thesis

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# CHAPTER 1
# ABSTRACT

Demand for wireless systems is steadily rising, and eventually the available spectrum resources would not be enough. The spectrum hole (also known as the unoccupied spectrum) must be located and used to its fullest potential in order to meet the demand for wireless systems. A gadget called Cognitive Radio (CR) uses a variety of detectors to intelligently sense the spectrum. The precise detector should be used for spectrum sensing based on the complexity and licensed user's data present with CR. We have primarily employed the energy detector (ED) spectrum sensing technique to address and resolve ED at low SNR issues. Different receiver operating characteristics have shown that the Improved Energy Detector (IED) and Variable Threshold Energy Detector (VTED) perform better than the standard ED approach. It has been demonstrated that for an optimal number of cooperative users of 10,OR logic rather than AND logic provides probability of detection ($P_D$) greater than 0.9 in a cooperative spectrum sensing (CSS) environment. Results have demonstrated that VTED technique, which has a higher probability of detection, or greater than 0.9 for cognitive radio networks, overcomes the low SNR region problem of regular ED technique. Additionally, MD is suggested for SISO and MIMO Rayleigh fading channels with and without a CSS environment. $P_D$ above 0.9 and probability of false alarm ($P_{FA}$) to 0.1 are also results of MD.

To determine the spectrum hole from the available spectrum resources, a Hybrid Detector (HD) is suggested. An ED and MD serve as the foundation for HD design. HD is able to sense the signal more precisely than a single detector like an ED or MD. HD is compatible with both scenarios, whether or not Primary User (PU) data is accessible. HD is examined in both cooperative spectrum sensing (CSS)-enabled and non-enabled heterogeneous situations. Under low SNR walls, CSS has implemented OR, AND, and majority schemes using 4 users. For each CSS algorithm in the HD model, the $P_D$ is maximized to 1 and $P_{FA}$ is minimized to 0 under low SNR conditions. The IEEE Wireless Regional Area Network (WRAN) 802.22 standard for accessing TV spectrum holes is used to guide the selection of standards for the HD.

# CHAPTER 2
# INTRODUCTION

Spectrum usage has become a key goal for emerging technology because of the rising demand from wireless consumers. To make the most of the current spectrum resources, the proper sensing approach should be used. The goal of Cognitive Radio (CR) is to sense the desired spectrum. Techniques for Spectrum Sensing (SS) are numerous. This thesis examines Cooperative Spectrum Sensing (CSS) for Cognitive Radio Networks (CRNs) by fusing different spectrum sensing detectors. The terms "CR" and "Dynamic Spectrum Access (DSA) technology" are defined in Section 2.1.

## 2.1. COGNITIVE RADIO (CR) & DYNAMIC SPECTRUM ACCESS (DSA)

Mitola [1] first developed cognitive radio in 1999 as part of his PhD thesis. "CR is a smart radio that runs on software and modifies its parameters dependent on the surrounding environment", is an example of how to define CR. CR does not interfere with the existing system when it is in operation. By regularly sensing on the desired channel, CR is used to locate the vacant spectrum on the licenced spectrum resources that are readily available. When the desired channel is discovered to be free, CR uses DSA technology to access it. According to Symon Haykin [2], the CR accesses the spectrum (which is free during that time period) wirelessly and intelligently. When CR functions in a certain area, it modifies its parameters and environment to suit the situation. The functions and uses of CR are numerous. Adaptability and reconfigurability are CR's key benefits, making it crucial for spectrum sensing approaches.

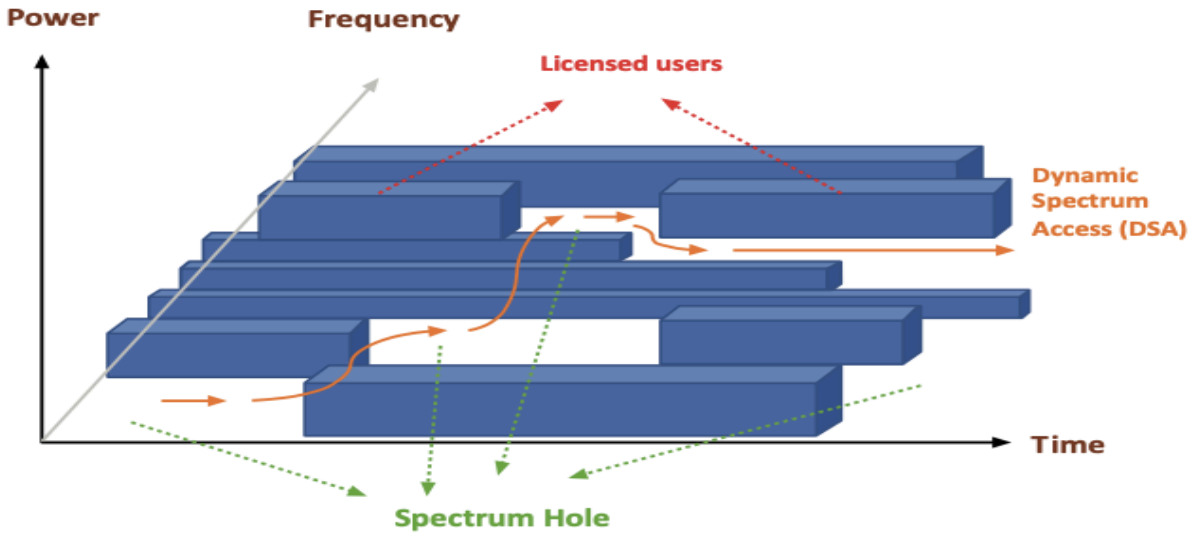


**Figure 2.1.1** DSA can be used to replace a spectrum hole.

On the licenced users spectrum, TV white spaces are produced as a result of the changeover from analogue to digital television. Federal Communication Commission (FCC) [3] issued an announcement stating that licenced users should not be got interference while using TV white space periodically. DSA is a technique for dynamically accessing the spectrum. Figure 2.1.1 demonstrates the replacement of the spectrum hole using DSA [4,5].

Using DSA, CR has emerged as a crucial tool for detecting the licenced user's spectrum without interfering with their transmission. Major tasks [6] of the CR include spectrum sensing, spectrum analysis, spectrum adaptation, and spectrum reasoning. The complete CR process cycle is depicted in Figure 2.1.2.

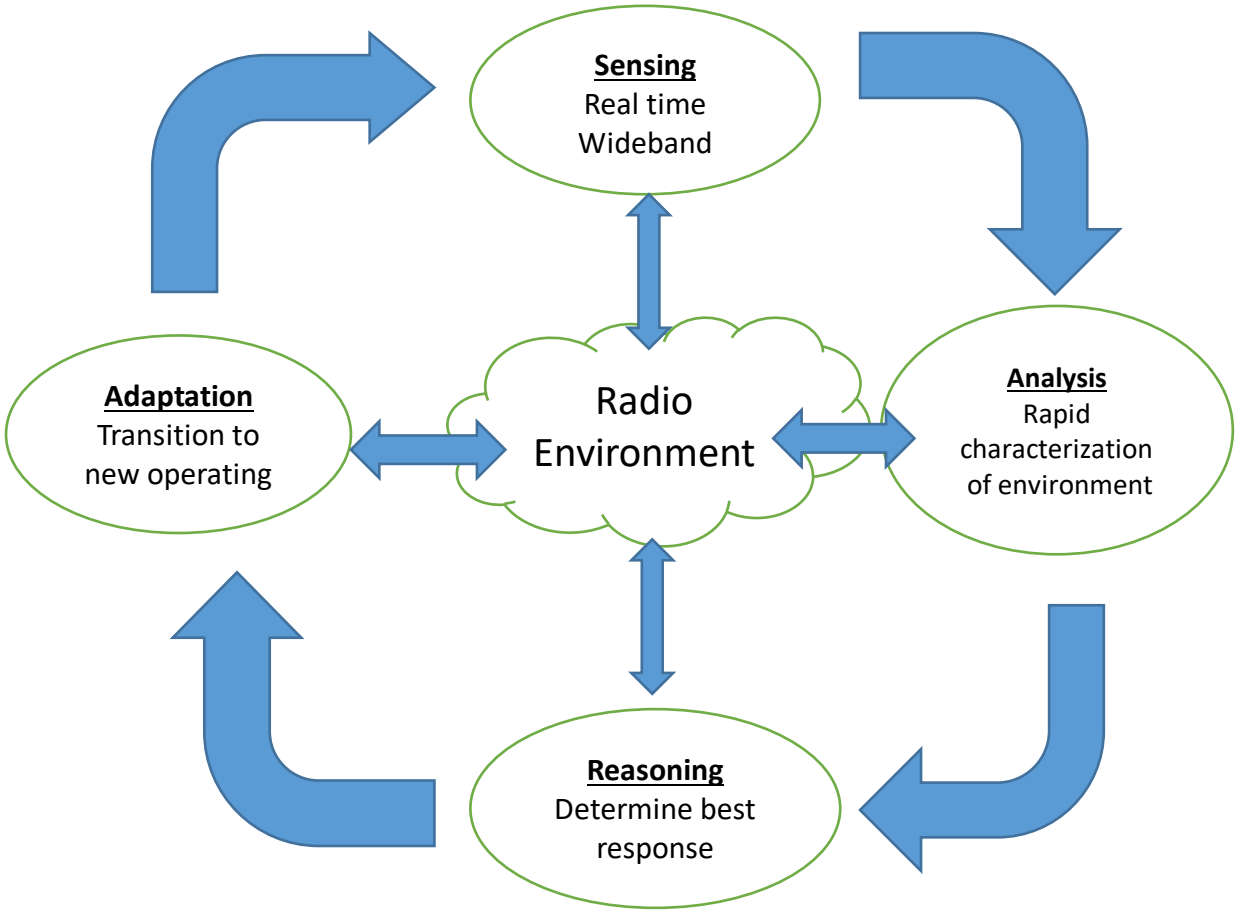


**Figure 2.1.2** Functions of Cognitive Radio

The requirements and specifications based on the IEEE 802.22 WRAN standard have been emphasized and discussed in section 2.2.

## 2.2 IEEE 802.22 WRAN STANDARD

To utilise TV white spaces [5,7] dynamically, IEEE standard 802.22 Wireless Regional Area Network (WRAN) has been introduced. For accessing empty TV channel slots, this standard provides internet access to remote places. Secondary users (SUs) can detect the 54 MHz and 862 MHz TV frequency channels. There should not be any disturbance with primary users (PUs) while SU is using these TV channels. Figure 2.2. depicts the case study of 802.22 WRAN in the area between the Base Station (BS) and the WRAN cell's limits, which is 33 to 100 km. The spectrum is used for TV through BS in that CR cell area, which has access to more network connections per channel. This network is utilised by WRAN Consumer Premises Equipment (CPE). The sensing parameters focused in this thesis are based on IEEE 802.22 WRAN standard.

The 802.22 WRAN standard spectrum sensing criteria are shown in Table 2.2. This work focuses on the 802.22 WRAN requirements to create the spectrum sensing models, such as the worst SNR, Probability of Detection ($P_D$), and Probability of False Alarm ($P_{FA}$).

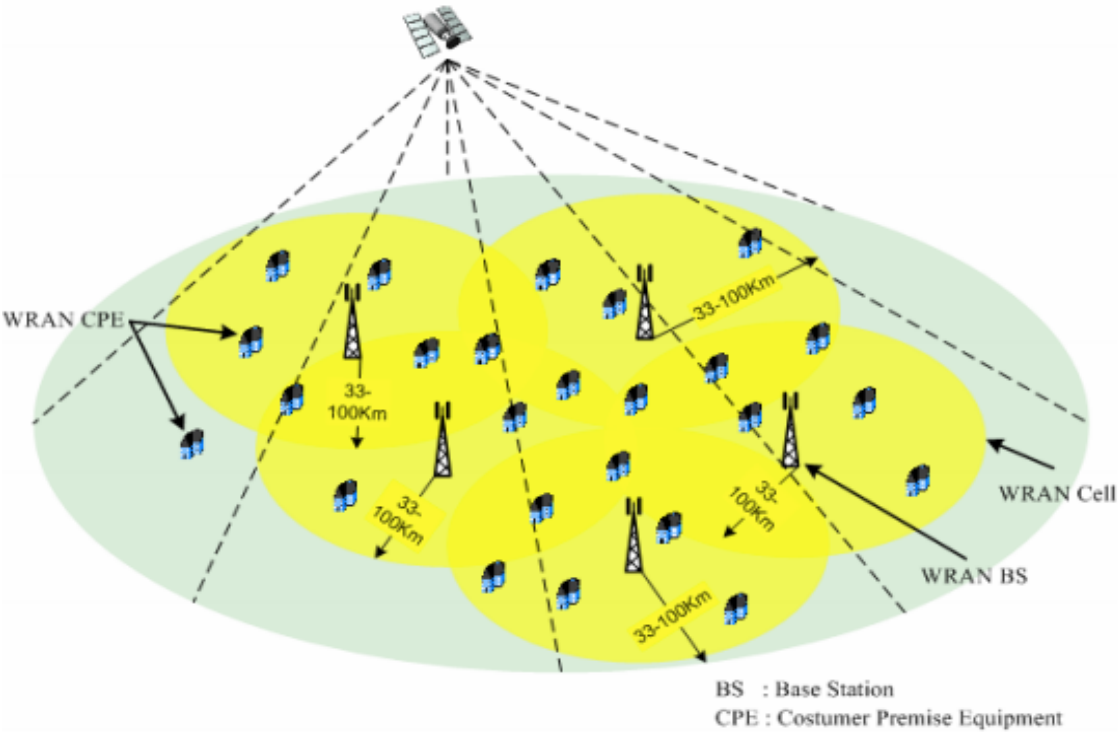


**Figure 2.2** 802.22 WRAN standard case study

**Table 2.2** Spectrum sensing criteria for 802.22 WRAN standard

| **Criteria** | **Digital TV** | **Wireless Microphone** |
|---|---|---|
| Time for channel to identify | ≤ 2sec | ≤ 2sec |
| Time for channel to transmission | 2 sec | 2 sec |
| Detection threshold | -116dBm (over 6Mhz) | -107dBm (over 200kHz) |
| Probability of Detection ($P_D$) | 0.9 | 0.9 |
| Probability of False Alarm ($P_{FA}$) | 0.1 | 0.1 |
| SNR | -20 dB | -12 dB |

## 2.3 DETECTION OF PRIMARY (LICENSED) USER SIGNAL

To make use of the primary (licensed) user's spectrum, there is a need to search for a spectrum gap. Once SU has located a gap in the spectrum, SU broadcasts via the CR method without interfering with PU activities. Each of the two binary hypotheses - one for the case of just noise (H0), and the other for the case of both noise and signal (H1) - is represented in Eq. (2.1),

H0: Only noise &

H1: Primary's signal is present + Noise (2.1)

PU's signal S(t), Noise n(t), are the signals received by aw2CR received, and Y(t) test statistics Eq. (1.1 ) can be expressed as

$$H0: Y(t) = n(t) \quad (2.2)$$
$$H1: Y(t) = S(t) + n(t) \quad (2.3)$$

Two distinct hypotheses are depicted in Eqs. (2.2) and (2.3), with H0 having only noise n(t) and H1 having both noise n(t) and signal S(t).

There are two potential issues (errors) when using the above two hypotheses. Once information acquired through CR, H0 is true however detector declares it as H1. This is called a Type 1 error. If type 1 error occurs in CR networks, it prevents the network from using the free channel. A signal transmission opportunity is lost in a Type 1 error. Type 1 error is also known as Probability of false alarm ($P_{FA}$). In a different instance, the detector claims that H0 is true even though H1 is actually true. This is called a Type 2 error. If Type 2 error occurs, it interferes with the PU signal. Therefore we should avoid such Type 2 errors happening in the networks. Type 2 error is also known as probability of miss detection ($P_{MD}$). The sum of $P_{MD}$ and $P_D$ is 1. The $P_D$ increases as $P_{MD}$ decreases, resulting in effective spectrum utilisation. Figure 2.3 displays the probability of false alarm ($P_{FA}$) vs. probability of detection ($P_D$) using receiver operating characteristics (ROC) graph at -20 dB SNR.

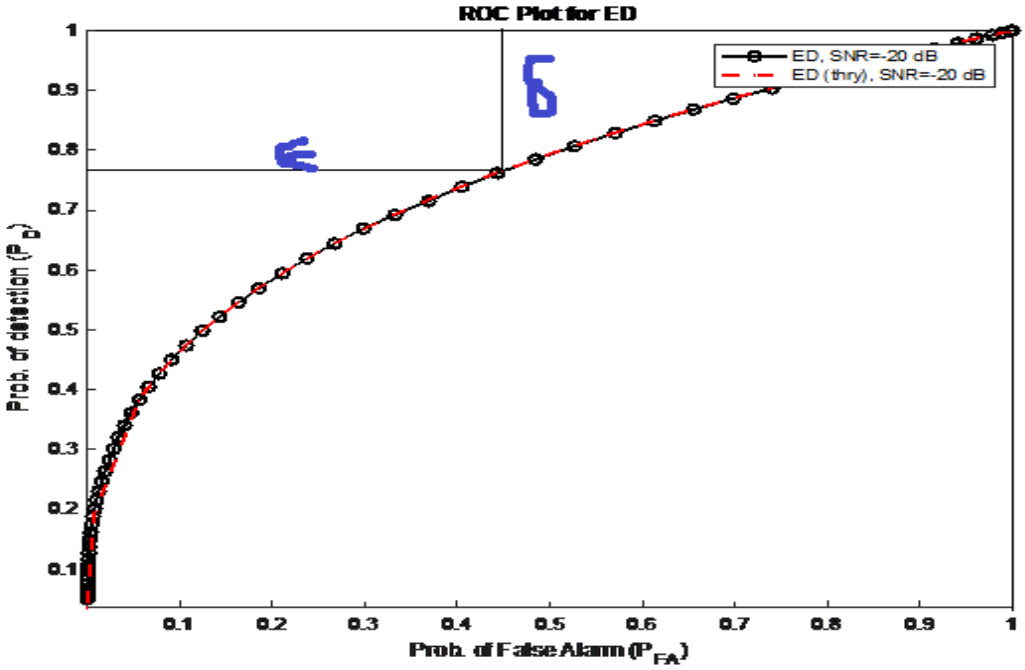


**Figure 2.3** Receiver Operating Characteristics example with -20 dB SNR

The subsequent Eq. (2.4) and (2.5) are Type 1 & Type 2 error respectively ,

Type 1 ($\epsilon$ ) Error ,

$$\epsilon = \text{Probability of False Alarm} = \text{Probability [Decide H1|H0]} \quad (2.4)$$

Type 2 ($\delta$) Error,

$$\delta = \text{Probability of Miss Detection} = \text{Probability [Decide H0|H1]} \quad (2.5)$$

The following Section 2.4 illustrates various spectrum sensing techniques and their comparison based on energy consumption, SNR etc.

## 2.4. SPECTRUM SENSING TECHNIQUES

To further access the spectrum of licensed users, CR's primary responsibility is spectrum sensing (SS). The main goal of SS is to reduce complexity and the likelihood of false alarms while maximizing the likelihood of detection. Figure 2.4 depicts the classification of SS into three basic categories of detection techniques: Energy Detector (ED), Matched Detector (MD), and Cyclostationary Feature Detection (CFD). Each SS technique has benefits and drawbacks.

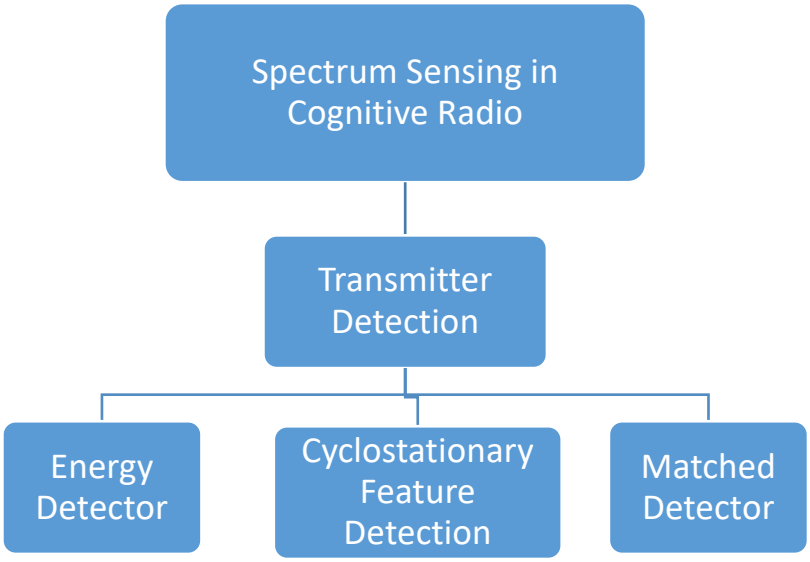


**Figure 2.4** Classification of Spectrum Sensing Techniques

A comparison of the three main SS approaches is presented in Table 2.4. Based on many factors, including implementation difficulty, poor SNR wall suffering, energy expenditure, and delay generated, ED, MD, and CFD are reviewed.

**Table 2.4.1** Comparison of the main spectrum sensing methods [8]

| **Spectrum Sensing Technique** | **Complexity in implementation** | **PU's Information needed** | **Low SNR Wall problem** | **Consumption of Energy** | **Delay** |
|---|---|---|---|---|---|
| Energy Detector (ED) | Low | No | Yes | Low | Less |
| Matched Detector (MD) | Moderate | Yes | No | Average | Moderate |
| Cyclostationary Feature Detector (CFD) | High | Yes | No | High | High |

In this thesis, ED and MD are primarily focused as spectrum sensing methods for cooperative spectrum sensing (CSS) environments. The thesis' major goal is described chapter 3.

# CHAPTER 3

# OBJECTIVES

To measure the accomplishment of the spectrum sensing method, two key parameters are the probability of detection ($P_D$) and the probability of false alarm ($P_{FA}$). Higher $P_D$ indicates stronger protection of PU. While lesser the false alarm, more opportunistic spectrum access for SUs are available and the channel can be reused when it is available. There are many spectrum sensing techniques available among which here is focused on Energy Detector (ED), a non-coherent technique. Due to its less complexity and easy implementation, ED has been widely used for signal detection of the primary signal. There is a drawback of ED when it employs low SNR values, its being difficult to distinguish between noise and primary signal. Also, there can be hidden nodes available on the network, which cannot be identified by one CR user. This leads to adding cooperative sensing along with normal spectrum sensing techniques. In cooperative spectrum sensing (CSS) [9], decisions can be taken out through observation based on the number of CRs reported information. Figure 3.1 shows the secondary user (CR user) transmission range and primary user transmission range through dotted line circles where the secondary user signal causes interference to the primary receiver due to not detecting of primary user's transmitter which is located outside of the CR transmission range. This problem is called an unknown node issue which could be overcome by CSS.

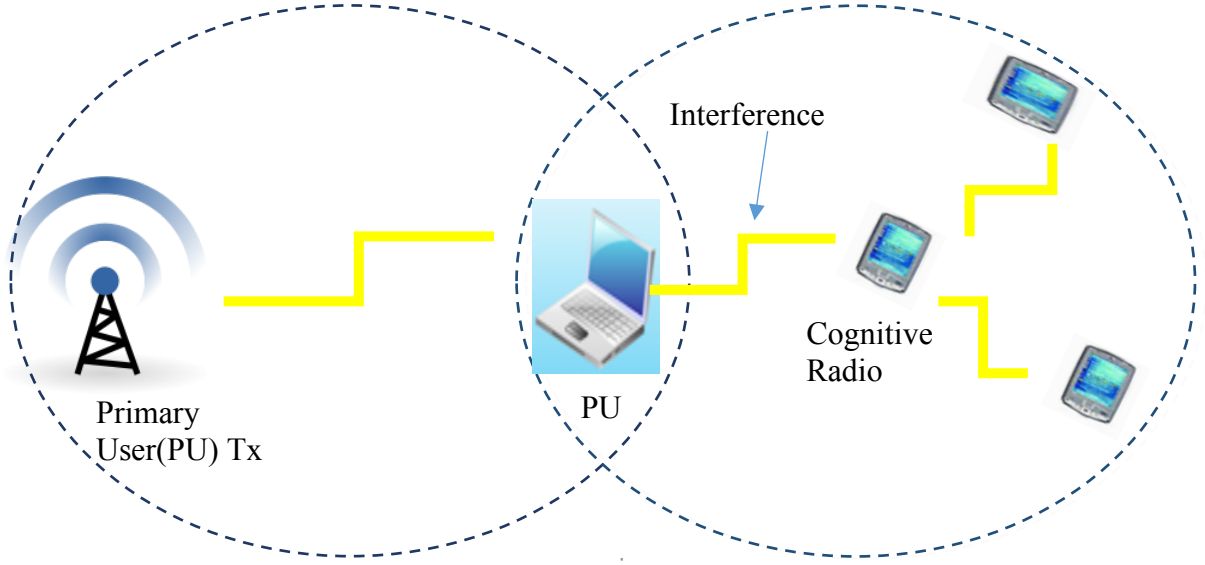


**Figure 3.1** In a cognitive radio system, hidden primary user.

To overcome the hidden PU transmitter problem in CR systems, CSS is widely used along with different SS techniques. CSS can improve the performance of detectors by reducing interference, shadowing, receiver uncertainty, and other problems. In CSS [10], several CR users report their decision to the fusion Centre (FC), and decisions are taken by the FC globally using AND, OR, or majority rule algorithms of CSS. This is known as the centralized CSS approach. In a distributed approach, all CR users share their information directly, and each CR user makes their own decision. The distributed approach is characterized by the absence of a fusion centre and this can reduce the sensing time compared with the centralized approach.

Objectives of our research work are

- Analyze various SS techniques for CRNs
- Optimization of the chosen detectors to utilize TV white spaces under 802.22 WRAN standard.
- Implement best method for SS in CRN under less complexity when PU information is not available - (ED), reduce low SNR problem of ED using modified ED
- When PU info available, implement best MD which is more complex detector than ED , Add cooperative Spectrum Sensing
- Implement hybrid detector to enhance the results and reduce complexity under Rayleigh fading.

# CHAPTER 4
# LITERATURE REVIEW

The detection of a transmitter of PU's signal, and spectrum sensing techniques are focused on ED, MD and CFD in [27-28]. Through results, a comparison of these three SS techniques has been done. CFD has shown better results in terms of probability of detection and probability of false alarm at lower SNR values compared to the other two techniques. The only drawback of CFD is the required more processing time compared to the other two techniques.

Various spectrum sensing techniques are discussed in [11-14], based on complexity and SNR range, SS can be chosen appropriately. There are many spectrum sensing challenges and future surveys are discussed like sensing fusion, sensing decision, sensing optimization, hidden receiver problem, multiple CRs, Security, traffic modelling etc.

Major spectrum sensing techniques like ED, CFD and MD are discussed through their Simulink models and comparison obtained through various roc curves in [8,29]. ED is simple to construct while CFD and MD are difficult to construct as required PU's signal information. MD and CFD outperform best under low range SNR, while ED performs worst under low SNR.

Cooperative spectrum sensing (CSS) is used for heterogeneous cognitive radio networks. Under CSS, the hidden transmitter node of PU can identify through various cooperative users. Instead of a single CR user, multiple CRs report their sensing data to the Fusion Centre (FC) and the decision is taken based on different algorithms of centralized cooperative spectrum sensing. In [18-19], normal ED is also modified to get better results under the low SNR range. Under CSS, performance is always better than in non-CSS environments.

The most widely used SS technique ED is implemented under the low wall SNR range due to its easy implementation. Single user and multiuser performances are compared based on -20 dB worst SNR under the AWGN channel. Performance of ED was also evaluated under fading channel through data fusion and decision fusion algorithms in [15-17]. Complementary receiver operating characteristics were obtained to optimize the threshold performance.

Conventional ED is suffering from low SNR wall region operation. It's been difficult to understand the difference between noise and PU's signal energy (at -20 dB) SNR. Due to less complexity, ED is easily implementable. To overcome this low SNR wall problem of ED, improved ED (IED) is analyzed with fixed threshold values. Further by varying thresholds, the Variable threshold ED (VTED)/ dynamic threshold ED is also analyzed. In comparison with normal ED, improved ED and VTED perform better in terms of probability of detection and probability of false alarm at -20 dB SNR in [20-23].

The detection time is reduced when PU information is available, and MD, ED and CFD are analyzed at various threshold levels in [24-26].MD based SS is done in other cognitive radio networks, where it can detect the status and multiple power levels of PU for known and unknown channel phases.

In [30-31], test-based algorithms are used to sense the PU spectrum. Based on a received difference between the two sample means, it identifies whether the PU is present or absent. SISO and MIMO channel models are used over here.

From above all literature, the thesis work is focused on the ED spectrum sensing technique for cognitive radio networks. ED is analyzed under CSS environments under various fading channels. To overcome hidden PU's transmitter, CSS is focused on decision fusion methods. Performance of non-CSS and CSS are compared over here. Normal ED performance is enhanced with IED and VTED when ED operates under a low SNR range -20dB. Further to operate in regions where SNR is like -30dB, matched detector (MD) is analyzed under non CSS and CSS environments. To design the environment, single input single output (SISO) and multiple-input multiple-output (MIMO) channel models are used. Depending on the user's demand, complexity, various operating parameters, fading environments, non-CSS, CSS, PU information available or not, Hybrid Detector (HD) is proposed. Based on the selection of above all parameters, HD selects ED or MD spectrum sensing technique for cooperative sensing. The major performance parameters range SNR, Probability of detection, probability of false alarm, and bandwidth are focused on in this thesis to utilize TV white bands as per IEEE 802.22 WRAN standards [32-33].

**Table 4.1** Comparison of existing SS techniques based on parameters required for IEEE 802.22 WRAN standard.

| **Spectrum Sensing (SS) Technique** | **SNR Value in dB** | **Cooperative SS (CSS) technique and No. of users (M)** | **Sample Size (N)** | **Probability of Detection** | **Probability of False Alarm** |
|---|---|---|---|---|---|
| Efficient spectrum management techniques using adaptive ED [42] | -20 | No | 1000 | 0.6<br>0.58 | 0.01<br>0.1 |
| Efficient spectrum management techniques using adaptive MD [42] | -20 | No | 1000 | 0.54<br>0.55 | 0.1<br>0.01 |
| Enhanced Energy Detector using MD [ 43] | -10<br>-20 | No | 100 | 0.9<br>0.925 | 0.1<br>0.1 |
| Enhanced spectrum sensing based on Energy Detector [44] | -20 | No | 1000 | 0.4 | 0.01 |
| Fusion rule based dynamic grouping [45] | -20<br>-5 | Yes , M=15 | 4000 | 0.97 | 0.1 |
| Improved local spectrum sensing based fuzzy logic | -15<br>-10 | No | 1000 | 0.5<br>0.97 | 0.0001<br>0.0001 |

| | | | | | |
|---|---|---|---|---|---|
| detection [39] | | | | | |
| A multiple antenna CR for PU detection[38] | 15<br>0 | No | 1000 | 1<br>0.45 | 0.01<br>0.01 |
| Dynamic spectrum access using two stage SS [34] | 6 | No | 100 | 0.99 | 0.1 |
| CR using two stage SS [40] | -10 | No | 1000 | 0.99 | 0.1 |
| CFD and ED combined detection [41] | 10 | No | 1000 | 0.94 | 0.1 |
| ED with double thresholds[35] | 10 | No | 1000 | 0.85 | 0.1 |
| Improved Energy Detector [36] | 0<br>10 | NO | 1000 | 0.62<br>0.99 | 0.1<br>0.1 |
| Energy Detector using advanced sensing techniques [37] | -5<br>-5 | No | 1000 | 0.95<br>0.72 | 0.6<br>0.1 |

### 4.1 Research Gap

There is not much focused on 802.22 WRAN standard at -20 dB SNR, very few papers available and performance is not good at -20dB. ED has problem at low SNR regions, which need to be overcome. MD is also helpful low SNR regions and PU's information available. There is a need to improve existing techniques as per 802.22 WRAN standard, based on complexity and PU's information available or not. A fusion detector needs to be developed as per 802.22 WRAN specifications.

# CHAPTER 5
# CONTRIBUTION

The proposed block diagram of Cooperative Spectrum Sensing (CSS) for Cognitive Radio Networks (CRNs) using Hybrid Detector (HD) is shown in Figure 5. Under HD, ED or MD is implemented and selected based on PU's information available or not. The proposed HD model shows that 4 CR users are used in the CSS environment. The OR, AND and Majority rule are implemented to analyze 4 CR users. Further contribution of ED are shown in section 5.1 to 5.4; while contribution of MD are represented by section 5.5 and 5.6. At the end section 5.7 explains the contribution of HD

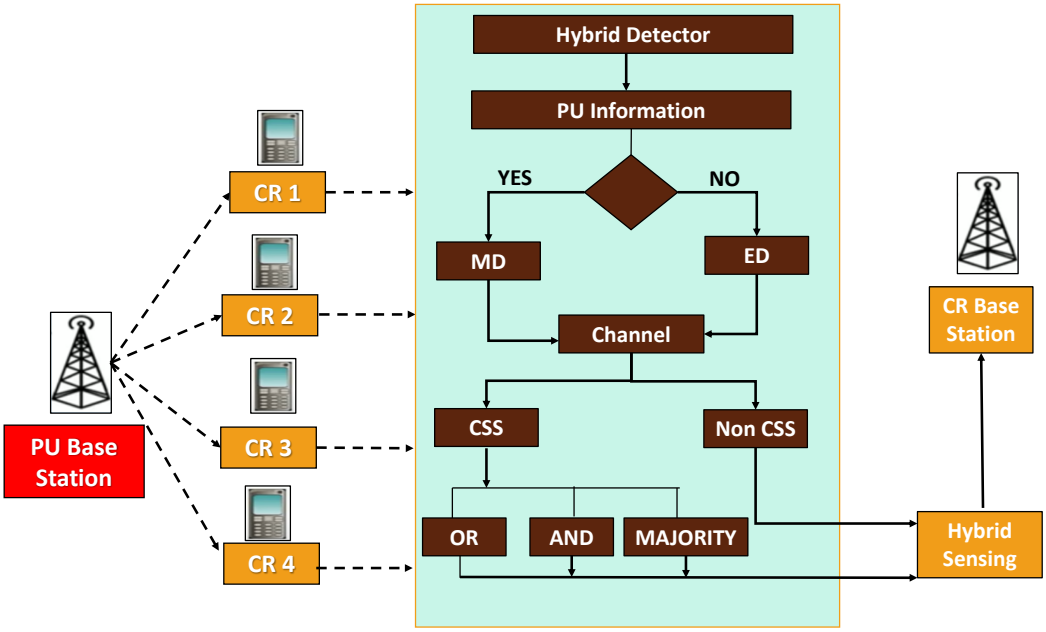


**Figure 5** Block Diagram of Cooperative Spectrum Sensing for Cognitive Radio Networks

## CONTRIBUTION 1 : ED

### 5.1 ED WITH SINGLE INPUT SINGLE OUTPUT (SISO) & MULTIPLE INPUT MULTIPLE (MIMO) ENVIRONMENT

Under the Rayleigh fading channel environment, the ED for single-input single-output (SISO) is demonstrated by considering the following mathematical parameters [47-49]. The Rayleigh fading channel coefficient h is unknown for the ED, and normalisation can be performed by

multiplying by $\frac{X^H}{||X||}$. Test statistics Y is again represented by multiplying with the X conjugate transpose ($X^H$) and dividing by the norm X (||X||) , where X is a transmitted pilot vector, and we obtain the new expressions in Eq. (5.1) and (5.2).

Null hypothesis $H_0$ : $\tilde{y} = \frac{X^H}{||X||} n = \tilde{n}$ (5.1)

Alternative hypothesis $H_1$: $\tilde{y} = \frac{X^H}{||X||}(H X + n)$

$= h\,||X|| + \tilde{n}$ (5.2)

where the noise $\tilde{n} \sim CN(0, \sigma 2)$, complex Gaussian with mean zero, variance σ2. To obtain the output $|\tilde{y}|^2$ with a threshold γ, the detector can be represented as,

$|\tilde{y}|^2 \geq \gamma \Rightarrow H1$ (5.3)

$|\tilde{y}|^2 < \gamma \Rightarrow H0$ (5.4)

From Eq. (5.3) and (5.4), if the received signal energy level is greater than the threshold γ, it indicates the presence of a PU signal, whereas if it is less than the threshold, it indicates that a PU signal is not present. The SISO wireless system is analysed to select a specific reference value for the given environment to detect the PU signal. The probability of a false alarm ($P_{FA}$) under the null hypothesis is given by Eq. (5.5),

$P_{FA} = Pr\,(|\tilde{y}|^2 \geq \gamma \mid H0)$

$= Pr\,(\frac{|\tilde{y}|^2}{\sigma^2/2} \geq \frac{\gamma}{\sigma^2/2})$

$= Q\chi_2^2\,(\frac{\gamma}{\sigma^2/2}) = \frac{1}{2} e^{-\gamma/\sigma^2}$ (5.5)

Where $Q\chi_2^2$ denotes the complementary cumulative distribution function (CCDF) of a $\chi_2^2$ random variable. The probability of detection ($P_D$) under the alternative hypothesis is given by Eq. (5.6),

$P_D = Pr\,(|\tilde{y}|^2 \geq \gamma \mid H1)$

$= Pr\,(\frac{|\tilde{y}|^2}{\frac{1}{2}||X||^2+\sigma^2} \geq \frac{\gamma}{\frac{1}{2}||X||^2+\sigma^2})$

$= Q\chi_2^2\,(\frac{\gamma}{\frac{1}{2}||X||^2+\sigma^2})$

$= \frac{1}{2} e^{-\gamma} \Big/ \frac{1}{2}||X||^2 + \sigma^2$ (5.6)

Similarly SISO, Multiple Input Multiple Output (MIMO) is also calculated by choosing receiving (r) x (t) transmitting antenna, which part is further explained in thesis.

## 5.2 IMPROVED ENERGY DETECTOR (IED)

In section 5.1, we have seen the normal energy detector through block representation and its working. This Normal Energy Detector suffers from low SNR values, which means Normal ED is unable to differentiate between the noise and primary signal under a low SNR region which can increase the probability of false alarm and reduce the probability of detection. To overcome this problem, we need to revise the ED algorithm. IED, the algorithm is described through Hypothesis, when output or test statistics is less than the threshold, IED compared with past signal energy and previous penultimate period also to reduce the probability of false alarm which is shown in figure 5.2.1 IED results are slightly improved than ED in terms of detection probability [24]. Figure 5.2.2 shows a comparison of Normal ED with IED, which reflects the $P_D$ is slightly better, but not good at -20 dB SNR region for IED.

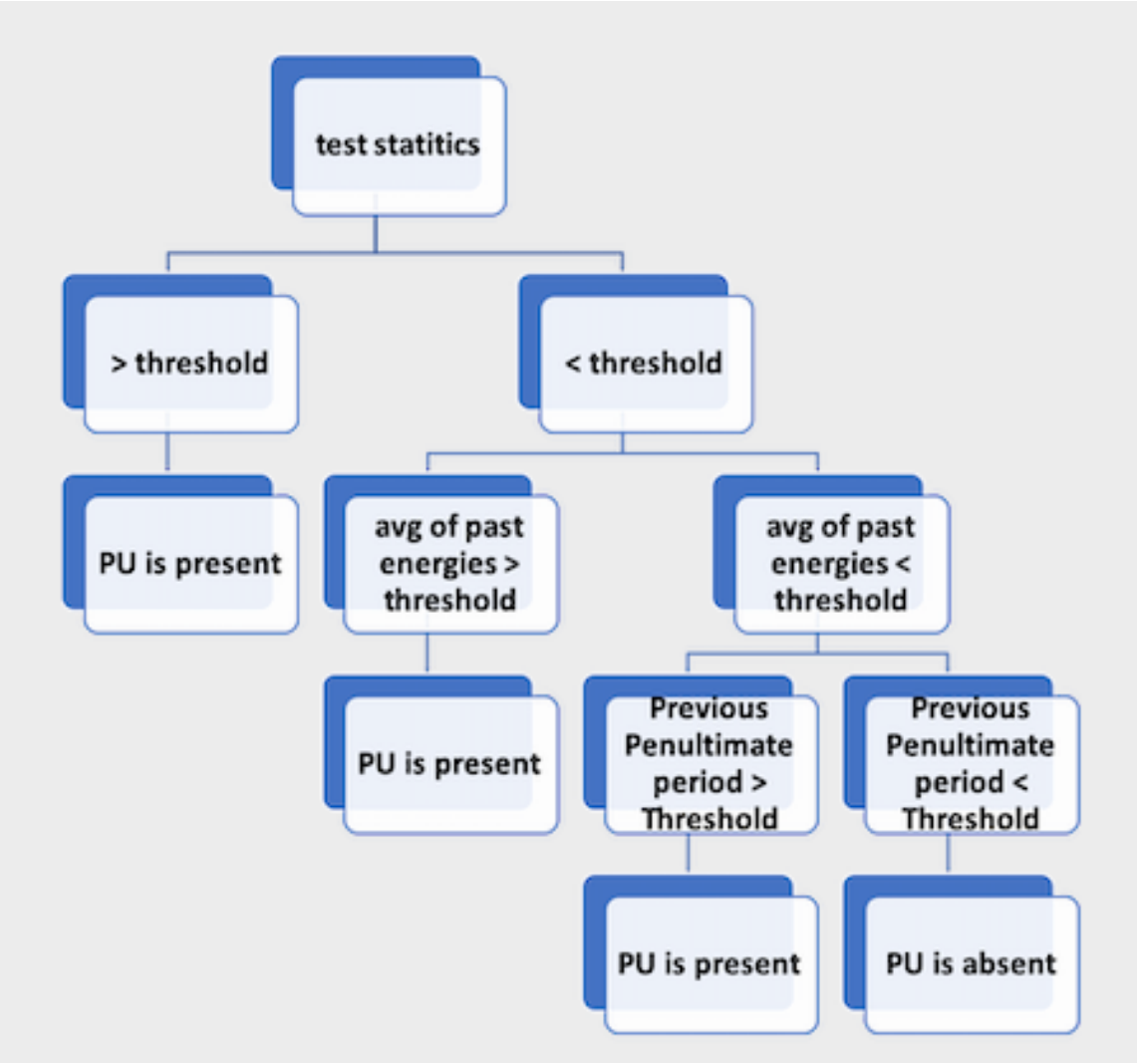


**Figure 5.2.1** IED algorithm

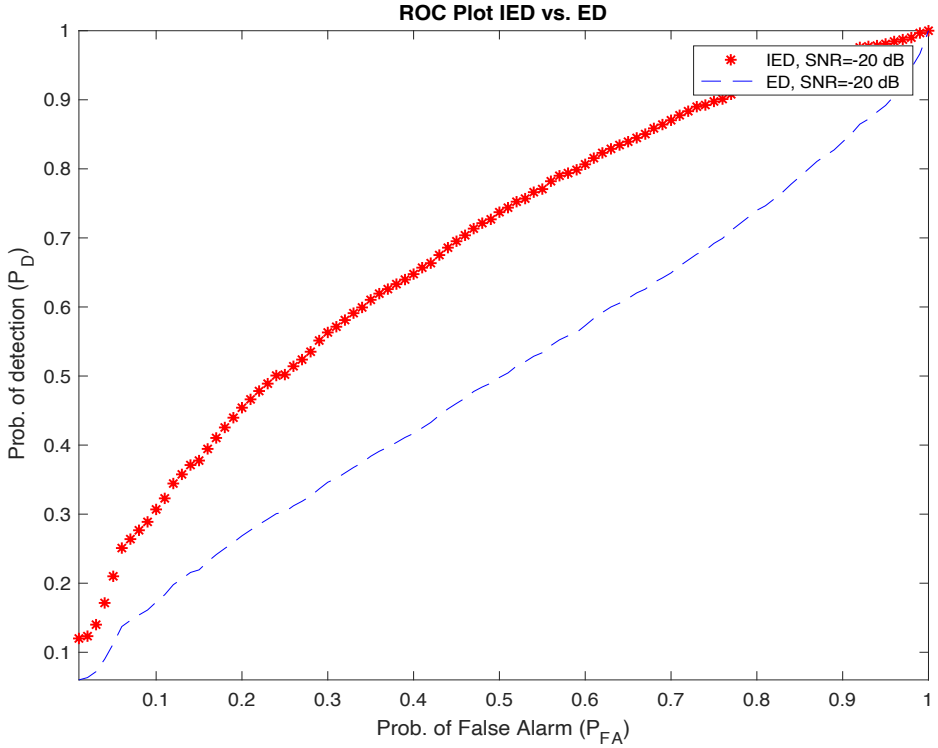


**Figure 5.2.2** Comparison of ED with IED at -20 dB at 1K sample size

## 5.3 VARIABLE THRESHOLD ENERGY DETECTOR (VTED)

In previous algorithms, the threshold was chosen at a fixed value if any change happens in noise power, it cannot be varied. Due to that at low SNR spectrum sensing accuracy could not be achieved. In [52,53] proposed double threshold method to reduce the uncertainty where the method deals with the energy of test statistics. If the energy of samples is less than a certain threshold, then the channel is free, but if the energy of samples is greater than a higher threshold, a channel is busy. But this type of double threshold algorithm performance is very poor in low SNR wall regions.

To overcome the noise power uncertainty, a variable threshold energy detector (VTED) is discussed in this section. In a variable threshold energy detector (VTED), a threshold is varied by the noise variance. Here Noise uncertainty factor can be calculated by dividing the maximum value of noise variance by the average value of all the noise variances. Using this noise uncertainty factor, a threshold is going to change dynamically according to the noise variance VTED reduces the low SNR problem (which is a disadvantage ) of ED better way compared to the ED & IED. There is another way to set two boundaries for a threshold which is called the double threshold ED model proposed in [13, 23]. Based on previous sensing history parameters, fixed lower and higher boundaries are set for detection of the primary user's signal which is not varying with a sudden change in the noise variance proposed in the VTED technique. Figure 5.3.1 shows a comparison of Normal ED with VTED, which reflects the $P_D$ is drastically improves, above 0.9 at -20 dB SNR region for VTED. Finally, figure 5.3.2 shows a comparison of Normal ED, IED (section 5.2) and VTED all together for small sample size 1k.

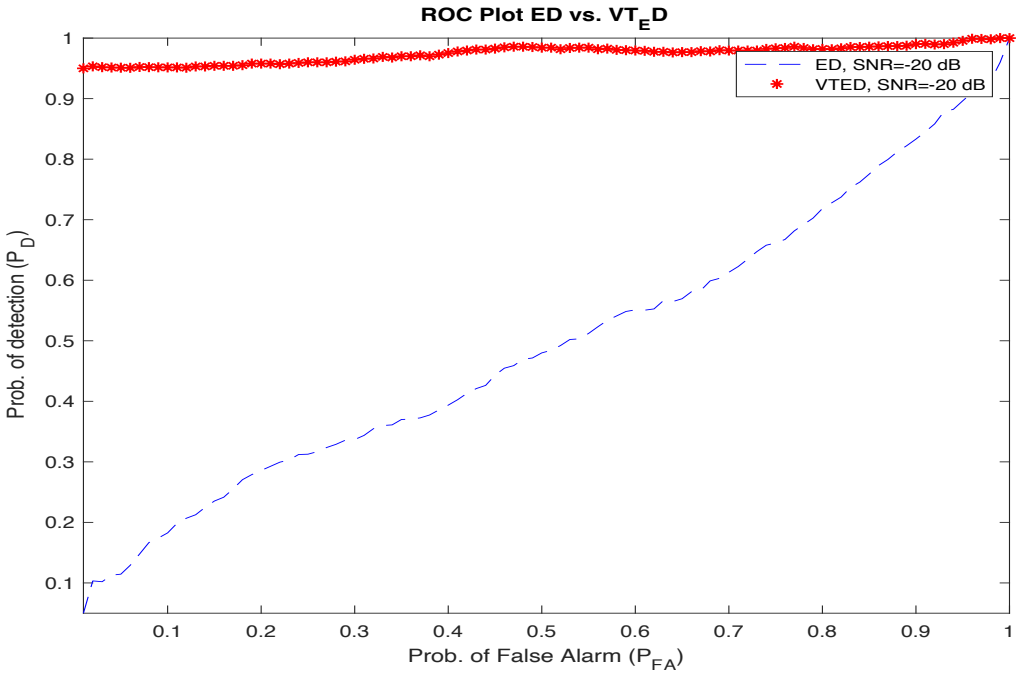


**Figure 5.3.1** Comparison of ED with VTED at -20 dB at 1K sample size

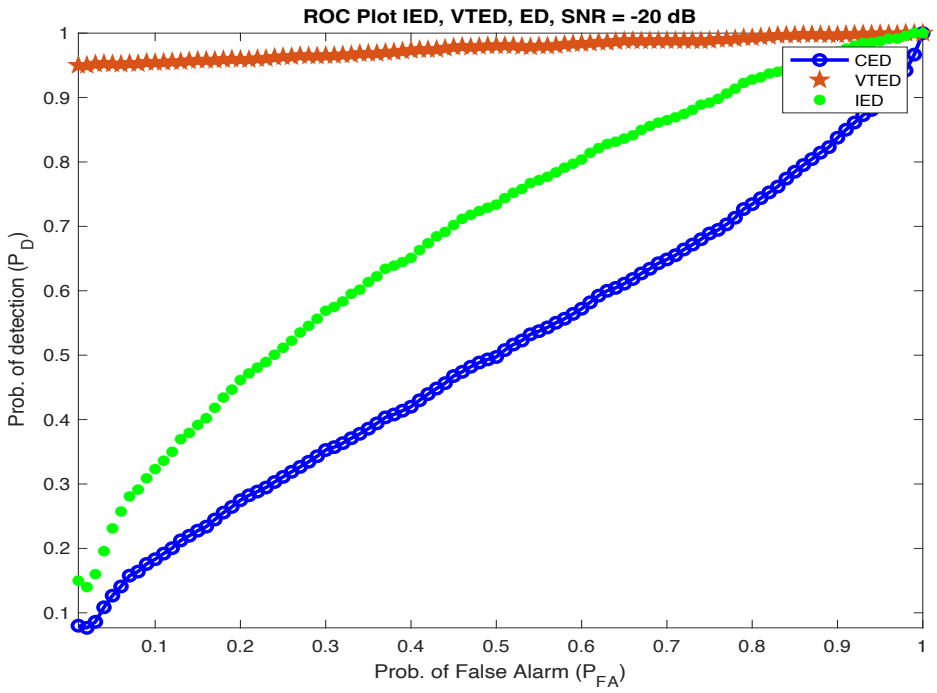


**Figure 5.3.2** Comparison of ED with IED &VTED at -20 dB

## 5.4. SUMMARY OF ED

Results of section 5.2 and 5.3 along with ED SISO and MIMO models with and without CSS (included from thesis) are shown in Table 5.4.1 to 5.4.3. In Table 5.4.4 shows a comparison of our work ED with the existing results.

**Table 5.4.1** Focused sensing parameters with sensing techniques (summary of section 5.1 and thesis results)

| **Spectrum sensing technique** | **SNR (dB)** | **$P_D$** | **$P_{FA}$** | **CSS decision & M** | **Pilot Symbols** |
|---|---|---|---|---|---|
| ED with Rayleigh SISO | -20 | 0.2 | 0.1 | No CSS | 100 |
| | -15 | 0.7 | 0.1 | | |
| | -10 | 0.9 | 0.1 | | |
| ED with Rayleigh SISO | -20 | 0.5 | 0 | No CSS | 250 |
| | -15 | 0.78 | 0 | | |
| | -10 | 0.9 | 0 | | |
| ED with Rayleigh SISO | -20 | 0.7 | 0 | No CSS | 500 |
| | -15 | 0.88 | 0 | | |
| | -10 | 0.96 | 0 | | |
| ED with Rayleigh SISO | -20 to -5 dB | CSS & 4 | | | |
| | | 0.8 | 0.1 | OR | 100 |
| | | 0.9 | 0.1 | AND | |
| | | 0.5 | 0.1 | Majority | |
| ED with Rayleigh SISO | -20 to -5 dB | CSS & 4 | | | |
| | | 0.92 | 0 | OR | 250 |
| | | 0.9 | 0 | AND | |
| | | 0.8 | 0.1 | Majority | |
| ED with Rayleigh SISO | -20 to -5 dB | CSS & 4 | | | |
| | | 1 | 0 | OR | 500 |

| | | | | | |
|---|---|---|---|---|---|
| | | 0.98 | 0 | AND | |
| | | 0.9 | 0 | Majority | |
| ED with Rayleigh SISO | -20 to -5 dB | CSS & 10 | | | |
| | | 0.9 | 0.1 | OR | 100 |
| | | 0.9 | 0.1 | AND | |
| | | 0.6 | 0.1 | Majority | |
| ED with Rayleigh SISO | -20 to -5 dB | CSS & 10 | | | |
| | | 1 | 0 | OR | 250 |
| | | 0.92 | 0 | AND | |
| | | 0.85 | 0 | Majority | |
| ED with Rayleigh SISO | -20 to -5 dB | CSS & 10 | | | |
| | | 1 | 0 | OR | 500 |
| | | 0.95 | 0 | AND | |
| | | 0.9 | 0 | Majority | |

**Table 5.4.2** Focused sensing parameters with sensing techniques (summary of section 5.1 and thesis results)

| **Spectrum sensing technique** | **SNR (dB)** | **$P_D$** | **$P_{FA}$** | **CSS decision & M** | **r x t matrix** |
|---|---|---|---|---|---|
| ED with Rayleigh MIMO | -20 | 0.1 | 0.1 | No CSS | 4 x 4 |
| | -10 | 0.15 | 0.1 | | |
| | 0 | 0.55 | 0.1 | | |
| | 10 | 0.98 | 0.1 | | |
| ED with Rayleigh MIMO | -20 | 0.1 | 0.1 | No CSS | 8 x 8 |
| | -10 | 0.18 | 0.1 | | |
| | 0 | 0.72 | 0.1 | | |

| | | | | | |
|---|---|---|---|---|---|
| | 10 | 1 | 0.1 | | |
| ED with Rayleigh MIMO | -20<br>-10<br>0<br>10 | 0.12<br>0.2<br>0.9<br>1 | 0.1<br>0.1<br>0.1<br>0.1 | No CSS | 16 x 16 |
| ED with Rayleigh MIMO | -20 to 10 dB | CSS & 4 | | | |
| | | 0.4 | 0.1 | OR | 4 x 4 |
| | | 0.3 | 0.1 | AND | |
| | | 0 | 0.1 | Majority | |
| ED with Rayleigh MIMO | -20 to 10 dB | CSS & 4 | | | |
| | | 0.5 | 0.1 | OR | 8 x 8 |
| | | 0.35 | 0.1 | AND | |
| | | 0.1 | 0.1 | Majority | |
| ED with Rayleigh MIMO | -20 to 10 dB | CSS & 4 | | | |
| | | 0.5 | 0.1 | OR | 16 x 16 |
| | | 0.4 | 0.1 | AND | |
| | | 0.25 | 0.1 | Majority | |
| ED with Rayleigh MIMO | -20 to 10 dB | CSS & 10 | | | |
| | | 0.3 | 0.1 | OR | 4 x 4 |
| | | 0.2 | 0.1 | AND | |
| | | 0.2 | 0.1 | Majority | |
| ED with Rayleigh MIMO | -20 to 10 dB | CSS & 10 | | | |
| | | 0.25 | 0.1 | OR | 8 x 8 |
| | | 0.4 | 0.1 | AND | |
| | | 0.3 | 0.1 | Majority | |
| ED with Rayleigh MIMO | -20 to 10 dB | CSS & 10 | | | |
| | | 0.25 | 0.1 | OR | 16 x 16 |

| | | | | | |
|---|---|---|---|---|---|
| | | 0.45 | 0.1 | AND | |
| | | 0.38 | 0.1 | Majority | |

**Table 5.4.3** Focused sensing parameters with sensing techniques (summary of section 5.2 & section 5.3 results)

| Spectrum sensing technique | SNR (dB ) | $P_D$ | $P_{FA}$ | Threshold | Sample size |
|---|---|---|---|---|---|
| Energy Detector (ED) | -20 | 0.15 | 0.1 | constant | 1000 |
| Improved Energy Detector | -20 dB | 0.3 | 0.1 | constant | 1000 |
| Variable Threshold Energy detector (VTED) | -20 dB | 0.95 | 0.1 | variable | 1000 |

**Table 5.4.4** Comparison ED with existing results

| Energy Detector (SS) Technique | SNR Value in dB | Cooperative SS (CSS) Technique and No. of Users (M) | Detector Used | Probability of Detection PD | Probability of False Alarm PFA |
|---|---|---|---|---|---|
| The proposed Energy detector (ED) model | −20 | Without CSS | ED with Rayleigh | 0.7 | 0.1 |
| The proposed Energy detector (ED) model | -20 to -5 | Yes and 4 & 10 | ED with Rayleigh | 1 / 0.98 | 0 |
| Heterogeneous CRN using Normalised ED [18 ] | −20 | Yes and 4 | LRT based NED | 0.6 | 0.1 |
| Spectrum Sensing over multipath fading channels for CRN [ 54] | -20 | Without CSS | NP using LLF+ED | 0.3 | 0.1 |
| Novel T test based spectrum sensing for SISO | -20 | Without CSS | TTBSS | 0.32 | 0.1 |

| | | | | | |
|---|---|---|---|---|---|
| & MIMO CRNs [30] | | | | | |
| Performance Analysis of new SS using multiantenna in CRNs [55] | -15 | Yes and 4 | ED with Rayleigh | 0.2 | 0.1 |
| Efficient Spectrum management techniques for CRN [42] | -20 | Yes and 2 | Adaptive ED | 0.58 | 0.1 |
| Enhanced SS based on ED [43] | -20 | NO | Adaptive ED | 0.4 | 0.01 |

**CONTRIBUTION 2 : MD**

## 5.5 MD WITH SINGLE INPUT SINGLE OUTPUT (SISO) & MULTIPLE INPUT MULTIPLE (MIMO) ENVIRONMENT

Roc curves are implemented practically and theoretically for MD under Rayleigh fading channel. Figure 5.5.1 shows results under CSS environments for MD under the SISO Rayleigh channel with 4 CR users. For SNR range -20 dB to -5 dB, 100 pilot symbols, AND, OR and Majority algorithms are implemented. OR and AND give better performance in terms of $P_D$ is 0.9 and $P_{FA}$ is 0.1. While majority rule performance is worst in the same condition. The MD for SISO and MIMO channel is tried for 250 and 500 pilot symbols which results are included in last summary table of MD from thesis work.

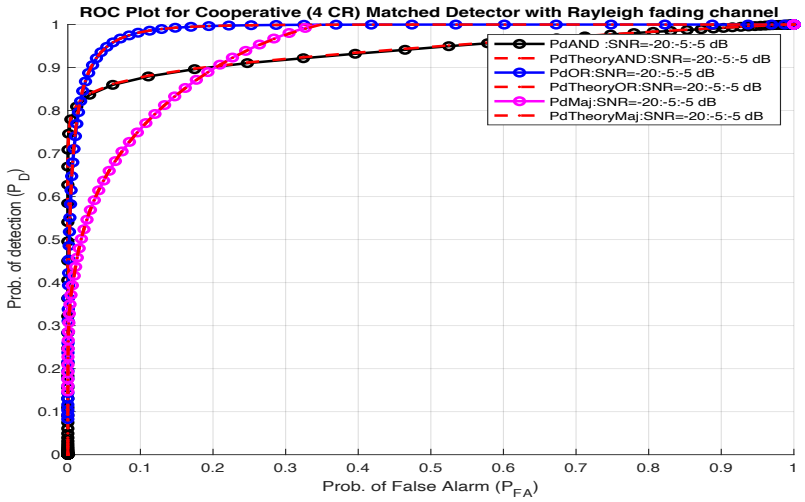


**Figure 5.5.1** $P_D$ Vs. $P_{FA}$ with CSS for P=100 pilot symbols with 4 CR

In Figure 5.5.2 MD has been simulated practically and theoretically for a cooperative spectrum sensing environment under Rayleigh fading MIMO wireless channels 4x4. In CSS, OR, AND and Majority rule have been tested under 4 & 10 CR users in heterogeneous networks. Results are shown for SNR range -20dB,-10dB, 0dB & 10dB where MD performance is better in terms of probability of detection with OR algorithm for all MIMO wireless channel models when 4 CR users are used.

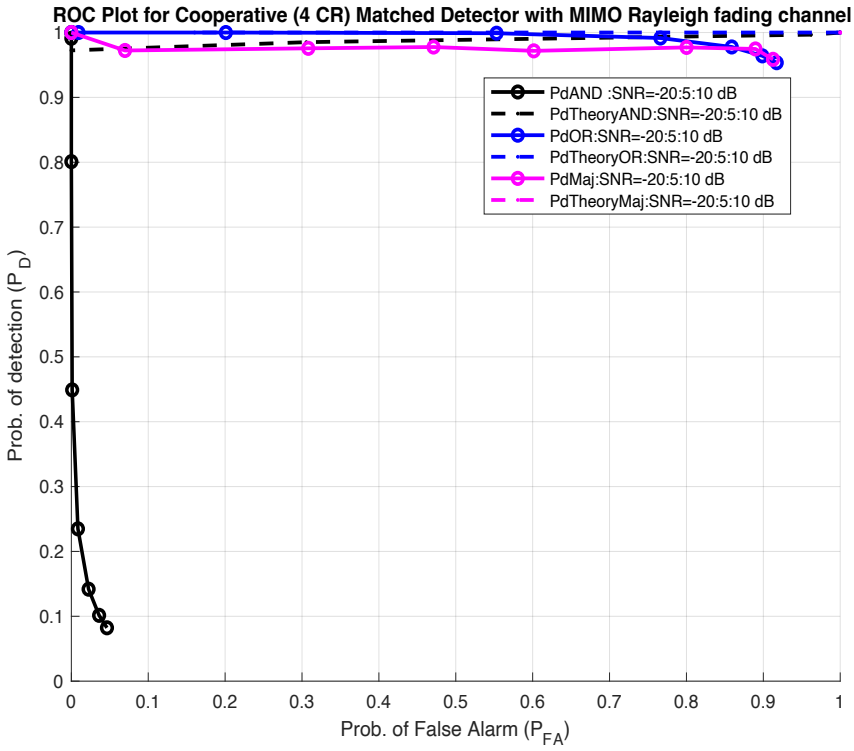


**Figure 5.5.2** $P_D$ Vs. $P_{FA}$ with CSS (4 CR) for 4x4 matrix.

## 5.6 SUMMARY OF MD

This summary of MD includes result of section 5.5 along with thesis work for MD models under SISO and MIMO included. Table 5.6.1 shows the results of MD with Rayleigh SISO channel under non CSS and CSS environments with 4 and 10 users. Similarly Table 5.6.2 shows the results of MD with Rayleigh MIMO channel under non CSS and CSS environments with 4 and 10 users. Table 5.6.3 shows the proposed model MD results with existing literature under CSS and Non CSS environments.

**Table 5.6.1** Focused sensing parameters with sensing techniques (summary of section 5.5 SISO results along with thesis results)

| **Technique for spectrum sensing** | **SNR (dB)** | **$P_D$** | **$P_{FA}$** | **CSS decision & M** | **Pilot Symbols** |
|---|---|---|---|---|---|
| MD with Rayleigh SISO | -20 | 0.6 | 0.1 | No CSS | 100 |
| | -15 | 0.82 | 0.1 | | |
| | -10 | 0.95 | 0.1 | | |
| MD with Rayleigh SISO | -20 | 0.65 | 0 | No CSS | 250 |
| | -15 | 0.7 | 0 | | |
| | -10 | 0.9 | 0 | | |
| MD with Rayleigh SISO | -20 | 0.8 | 0 | No CSS | 500 |
| | -15 | 0.7 | 0 | | |
| | -10 | 0.9 | 0 | | |
| MD with Rayleigh SISO | -20 to -5 dB | CSS & 4 | | | |
| | | 0.9 | 0 | OR | 100 |
| | | 0.84 | 0 | AND | |
| | | 0.5 | 0 | Majority | |
| MD with Rayleigh SISO | -20 to -5 dB | CSS & 4 | | | |
| | | 0.95 | 0 | OR | 250 |
| | | 0.9 | 0 | AND | |
| | | 0.4 | 0.1 | Majority | |
| MD with Rayleigh SISO | -20 to -5 dB | CSS & 4 | | | |
| | | 0.98 | 0 | OR | 500 |
| | | 0.92 | 0 | AND | |
| | | 0.3 | 0 | Majority | |

| | | | | | |
|---|---|---|---|---|---|
| MD with Rayleigh SISO | -20 to -5 dB | CSS & 10 | | | |
| | | **0.95** | **0** | **OR** | 100 |
| | | 0.65 | 0 | AND | |
| | | 0.65 | 0 | Majority | |
| MD with Rayleigh SISO | -20 to -5 dB | CSS & 10 | | | |
| | | **1** | **0** | **OR** | 250 |
| | | 0.8 | 0 | AND | |
| | | 0.85 | 0 | Majority | |
| MD with Rayleigh SISO | -20 to -5 dB | CSS & 10 | | | |
| | | **1** | **0** | **OR** | 500 |
| | | 0.85 | 0 | AND | |
| | | 0.7 | 0 | Majority | |

**Table 5.6.2** Focused sensing parameters with sensing techniques (summary of section 5.5 MIMO results along with thesis results)

| **Spectrum sensing technique** | **SNR (dB)** | **$P_D$** | **$P_{FA}$** | **CSS decision & M** | **Pilot Symbols** |
|---|---|---|---|---|---|
| MD with Rayleigh MIMO | -20 to 10 dB | CSS & 4 | | | |
| | | 1 | 0 | OR | 4 x 4 |
| | | 0 | 0 | AND | |
| | | 1 | 0 | Majority | |
| MD with Rayleigh MIMO | -20 to 10 dB | CSS & 4 | | | |
| | | 1 | 0 | OR | 8 x 8 |

| | | | | | |
|---|---|---|---|---|---|
| | | 0 | 0 | AND | |
| | | 1 | 0 | Majority | |
| MD with Rayleigh MIMO | -20 to 10 dB | CSS & 4 | | | |
| | | 1 | 0 | OR | 16 x 16 |
| | | 0 | 0 | AND | |
| | | 1 | 0 | Majority | |
| MD with Rayleigh MIMO | -20 to 10 dB | CSS & 10 | | | |
| | | 1 | 0 | OR | 4 x 4 |
| | | 0 | 0 | AND | |
| | | 0.9 | 0 | Majority | |
| MD with Rayleigh MIMO | -20 to 10 dB | CSS & 10 | | | |
| | | 1 | 0 | OR | 8 x 8 |
| | | 0 | 0 | AND | |
| | | 1 | 0 | Majority | |
| MD with Rayleigh MIMO | -20 to 10 dB | CSS & 10 | | | |
| | | 1 | 0 | OR | 16 x 16 |

| | | | | | |
|---|---|---|---|---|---|
| | | 0 | 0 | AND | |
| | | 0.9 | 0 | Majority | |

**Table 5.6.3** Comparison MD with existing results

| Matched Detector (SS) Technique | SNR Value in dB | Cooperative SS (CSS) Technique and No. of Users (M) | Detector Used | Probability of Detection $P_D$ | Probability of False Alarm $P_{FA}$ |
|---|---|---|---|---|---|
| The proposed Matched detector (MD) model | −20 | Without CSS | MD with Rayleigh | 0.7 | 0.1 |
| The proposed Matched detector (MD) model | -20 to -5 | Yes and 4 & 10 | MD with Rayleigh | 1 | 0 |
| MD based SS and Power level detection for CRN [27] | -15 | Without CSS | MD with Rayleigh | 0.9 | 0.1 |
| MD based SS for PU Multiple power levels [29 ] | -15 | Without CSS | MD with Rayleigh | 0.9 | 0.1 |
| Efficient Spectrum management techniques for CRN [34] | -20 | Yes and 2 | Adaptive MD | 0.54 | 0.1 |

**CONTRIBUTION 3 : HD**

## 5.7 HYBRID DETECTOR (HD)

Using Hybrid Detector (HD) spectrum sensing is done for Cognitive Radio Networks (CRNs). Sections 5.7.1 and 5.7.2 show the HD analysis for non-cooperative and cooperative sensing respectively.

### 5.7.1 Performance Analysis of HD for Non-CSS

The hybrid detector is designed with a non-cooperative spectrum sensing Rayleigh fading channel environment in this section. There are two possibilities either CR may have PU's information available for the operating region or may not. Based on the previous history of PU's

signal available with CR, HD can select MD in this scenario to better find the spectrum hole. If PU's information is not available with CR, HD can select ED. Below there are two case studies results shown as per randomisation of PU's signal info is available or not.

**Case 1:** Random variable Z = 0.7 and above (PU information not available), select Hybrid = ED

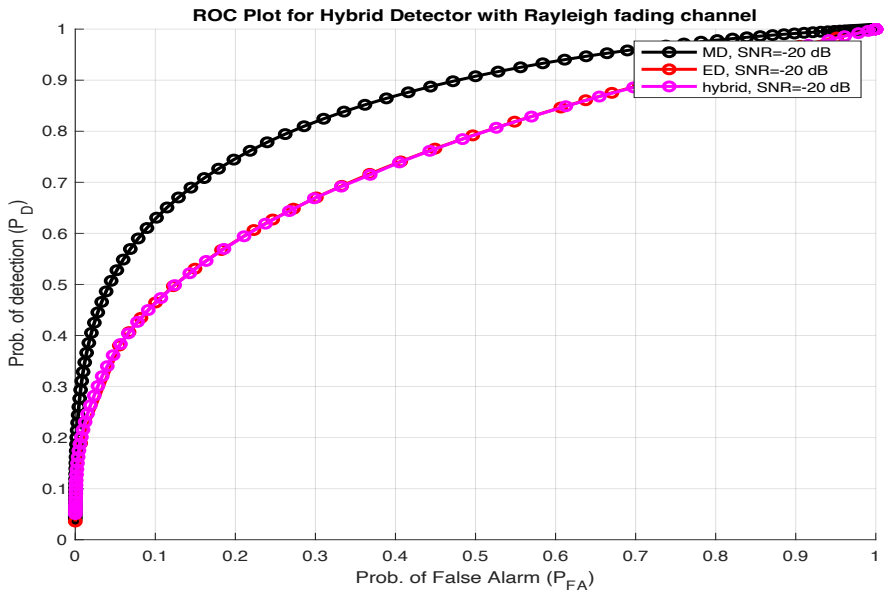


**Figure 5.7.1.1** Hybrid detector under Non-CSS for case 1

**Case 2:** Random variable Z = below 0.7(PU information available), select Hybrid =MD

Figure 5.7.1.1 & 5.7.1.2 represent the hybrid detector performance for case 1 and case 2 respectively under non-cooperative spectrum sensing For case study Z (random variable) probability is chosen between 0 to 1. When CR have PU's information, HD selects MD otherwise HD selects ED. HD is analysed under the worst SNR -20 dB with practical and theoretical results shown in the ROC curve in Figures 5.8.1.1 & 5.8.1.2. Table 5.7.1 shows a summary of section 5.7.1 results.

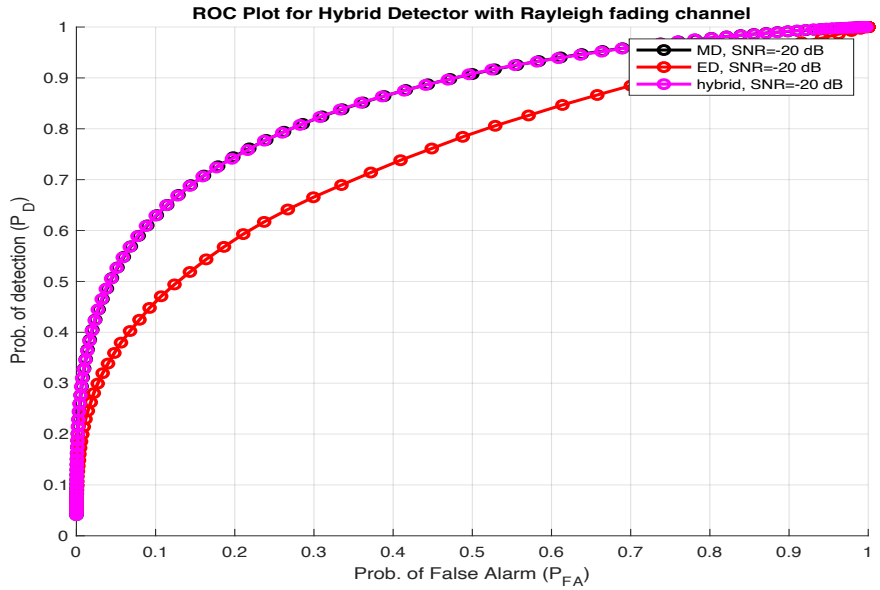


**Figure 5.7.1.2** Hybrid detector under non CSS for case 2

**Table 5.8.1** Hybrid Detector Performance Parameters under Non-CSS environment

| Case 1 : Select ED | Non-CSS | Case 2 : Select MD | Non-CSS |
|---|---|---|---|
| $P_D$ | 0.5 | $P_D$ | 0.6 |
| $P_{FA}$ | 0.1 | $P_{FA}$ | 0.1 |
| SNR (low range) | -20 dB | SNR (low range) | -20 dB |

### 5.7.2 Performance Analysis of HD for CSS

The hybrid detector is designed with a cooperative spectrum sensing Rayleigh fading channel environment in this section. OR, AND and Majority algorithms are used to design the CSS environment for different 4 CR users. Similarly, case 1 & case 2 of previous section 5.7.1, are discussed for the CSS environment.

**Case 1:** Random variable Z = 0.7 and above (PU information not available), select Hybrid = ED

Figures. 5.7.2.1, 5.7.2.2 & 5.7.2.3 represent the hybrid detector performance for case 1 with OR, AND and Majority decision under cooperative spectrum sensing with 4 CR users. Case 2 reflects if the variable Z is above 0.7 (i.e. 0.7 to up to 1), HD selects ED. HD is analysed under the worst SNR range of -20 dB to -5 dB for heterogeneous networks theoretically and practically.

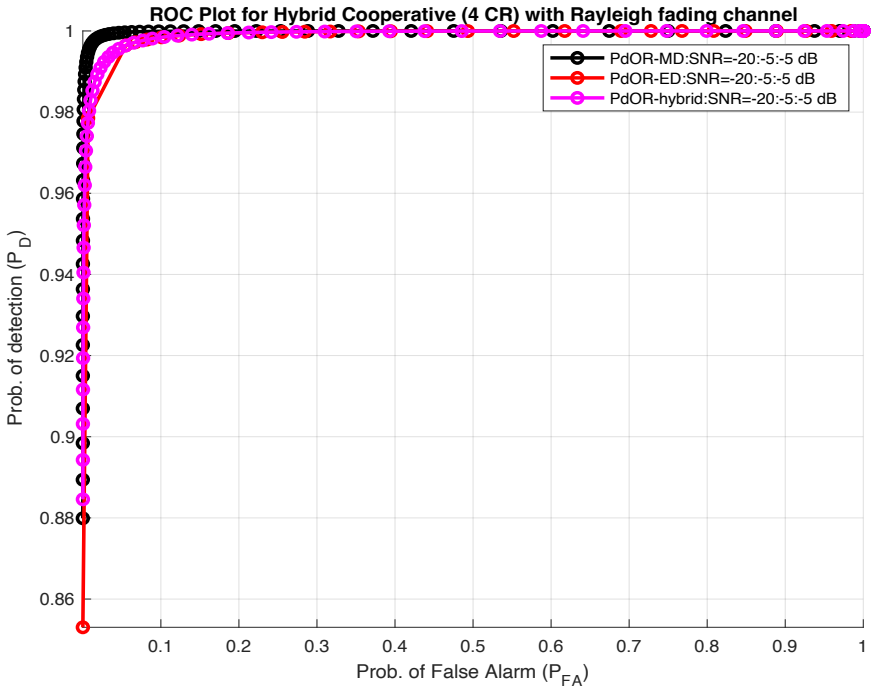


**Figure 5.7.2.1** Hybrid detector under CSS (4) - OR for case 1

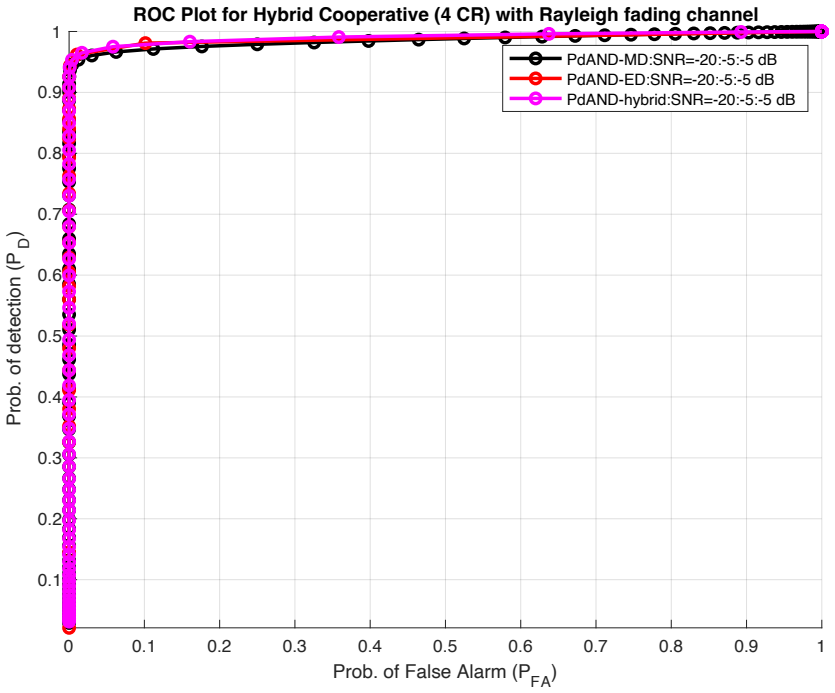


**Figure 5.7.2.2** Hybrid detector under CSS (4) – AND for case 1

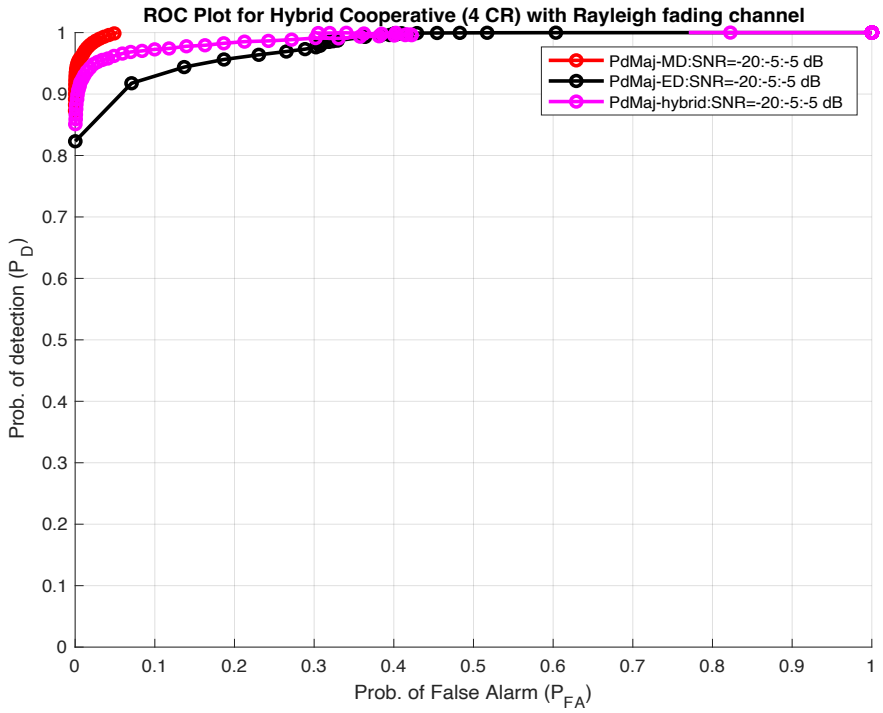


**Figure 5.7.2.3** Hybrid detector under CSS (4) – Majority for case 1

**Case 2:** Random variable Z = below 0.7 (PU information available), select Hybrid = MD

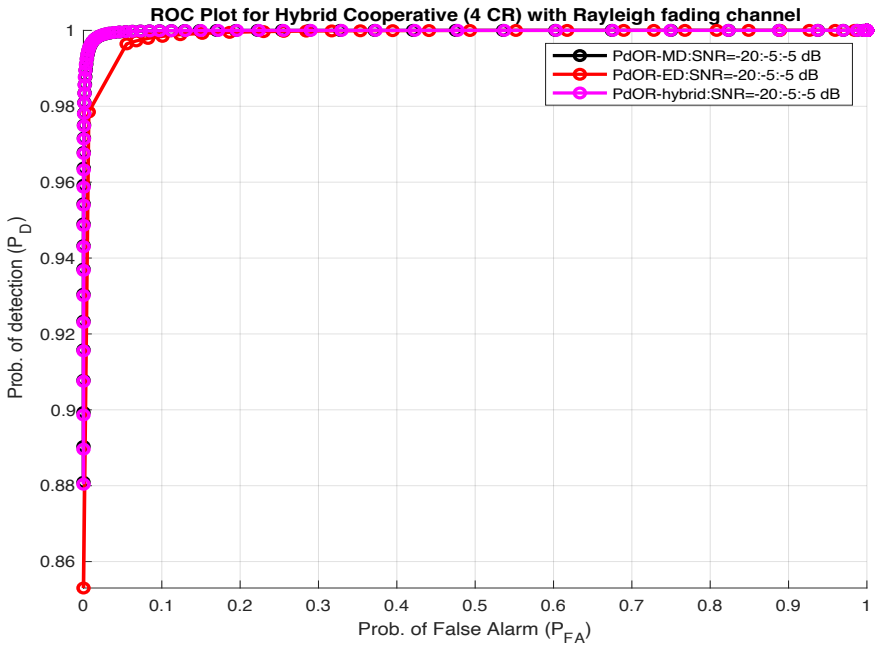


**Figure 5.7.2.4** Hybrid detector under CSS (4) - OR for case 2

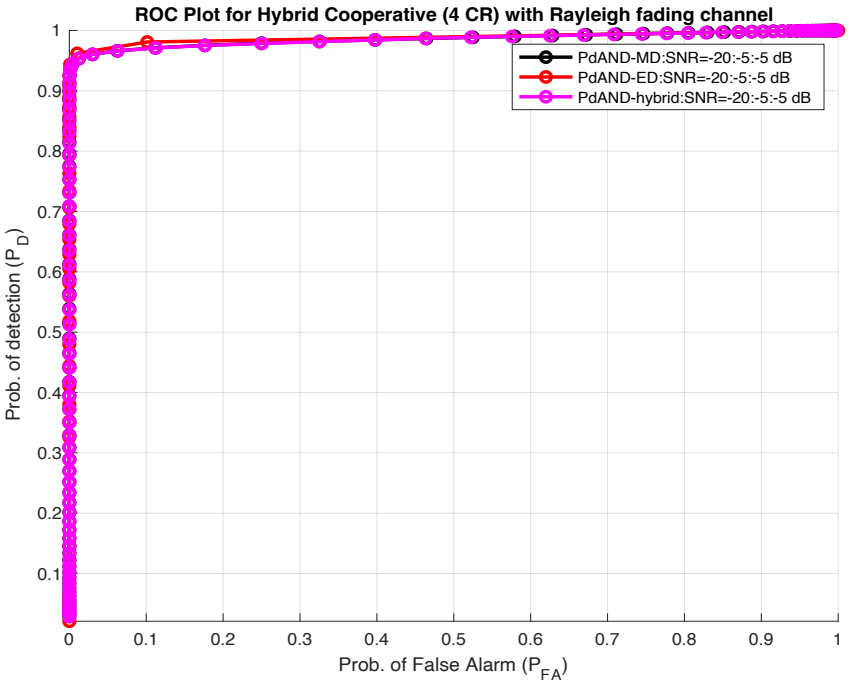
ROC Plot for Hybrid Cooperative (4 CR) with Rayleigh fading channel
PdAND-MD:SNR=-20:-5:-5 dB
PdAND-ED:SNR=-20:-5:-5 dB
PdAND-hybrid:SNR=-20:-5:-5 dB
Prob. of detection (P_D)
Prob. of False Alarm (P_FA)

**Figure 5.7.2.5** Hybrid detector under CSS (4) – AND for case 2

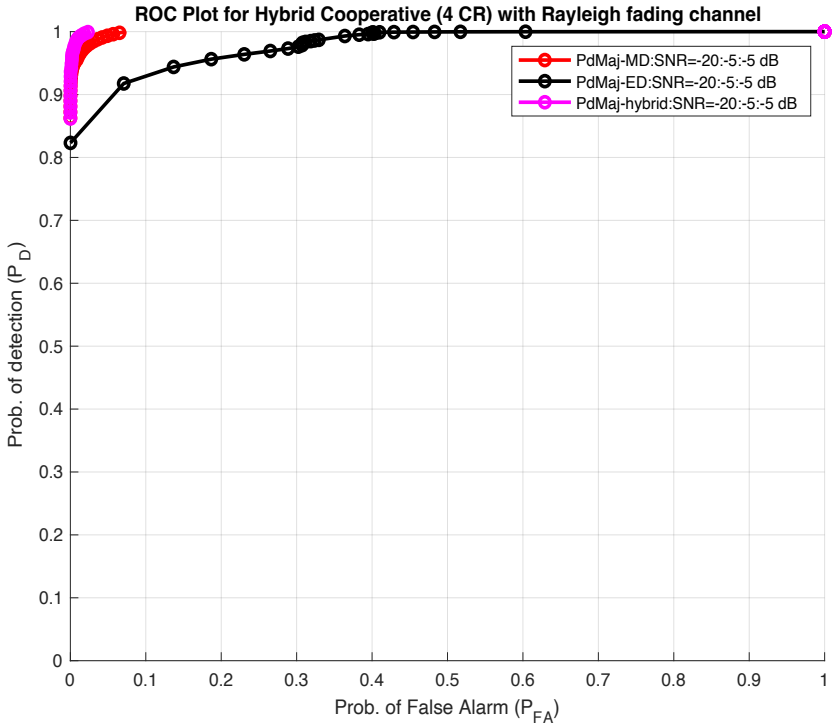
ROC Plot for Hybrid Cooperative (4 CR) with Rayleigh fading channel
PdMaj-MD:SNR=-20:-5:-5 dB
PdMaj-ED:SNR=-20:-5:-5 dB
PdMaj-hybrid:SNR=-20:-5:-5 dB
Prob. of detection (P_D)
Prob. of False Alarm (P_FA)

**Figure 5.7.2.6** Hybrid detector under CSS(4) – Majority for case 2

Figures. 5.7.2.4 , 5.7.2.5 & 5.7.2.6 represent the hybrid detector performance for case 2 with OR, AND and Majority decision under cooperative spectrum sensing with 4 CR users. Case 2 reflects if the variable Z is below 0.7 (i.e. 0 to up to 0.6) , HD selects MD. HD is also analysed under the worst SNR range of -20 dB to -5 dB for heterogeneous networks theoretically and practically. Below table 5.7.2 shows a summary of section 5.7.2 results.

**Table 5.7.2** Hybrid Detector Performance Parameters under CSS environment

| **Case 1 : Select ED** | **OR** | **AND** | **Majority** | **Case 2 : Select MD** | **OR** | **AND** | **Majority** |
|---|---|---|---|---|---|---|---|
| SNR (low range | -20 dB, -15 dB, -10 dB, -5 dB | | | SNR (low range | -20 dB, -15 dB, -10 dB, -5 dB | | |
| Cooperative Users (M) | 4 | | | Cooperative Users (M) | 4 | | |
| $P_D$ | 0.98 | 0.96 | 0.94 | $P_D$ | 1 | 0.96 | 0.88 |
| $P_{FA}$ | 0 | 0 | 0.1 | $P_{FA}$ | 0 | 0 | 0 |

In comparison with AND and Majority, OR decision provides the best probability of detection ($P_D$) i.e. nearer to 1 along with the probability of false alarm ($P_{FA}$) to almost 0. These are the requirement for the IEEE 802.22 WRAN standard to utilise the TV spectrum holes.

**Table 5.7.3** Comparison HD with existing results

| **Hybrid Detector (SS) Technique** | **SNR Value in dB** | **Cooperative SS (CSS) Technique and No. of Users (M)** | **Detector Used** | **Probability of Detection $P_D$** | **Probability of False Alarm $P_{FA}$** |
|---|---|---|---|---|---|
| The proposed Hybrid detector (HD) model | −20 | Yes and 4 | ED and MD | 1 | 0 |
| Improvement in SS using modified hybrid sensing [56] | 0 | Yes and 3 | MD and CFD | 0.82 | 0.001 |
| Hybrid sensing for band selection [57] | −20 | Yes and 10 | ED | 0.65 | 0.1 |

| | | | | | |
|---|---|---|---|---|---|
| Complexity reduction for CFD using improved hybrid sensing [58] | 0 | Yes and 3 | CFD and sliding DFT | 0.7 | 0.1 |
| Enhanced Energy Detector using MD [43] | -20 | No | Fusion ED+MD | 0.92 | 0.1 |
| Fusion rule based dynamic grouping [45] | -20 | Yes and M=15 | Fusion | 0.97 | 0.1 |
| Improved local spectrum sensing based fuzzy logic detection [39] | -15<br>-10 | No | Fuzzy logic | 0.5<br>0.97 | 0.0001<br>0.0001 |

OR algorithm provides the best detection probability ($P_D$), which is 1, and lowest false alarm probability ($P_{FA}$), which is zero, when compared to AND and Majority. These are needed for IEEE 802.22 WRAN to take use of the TV spectrum gaps. The results show that there is no need in modification in ED when HD is used.

# CHAPTER 6
# CONCLUSION

When the Detector operates in low SNR zones, its performance suffers. When there is a good SNR, Cognitive Radio Networks produce superior outcomes with spectrum sensing detectors in terms of PU signal detection. All detectors perform well when SNR is good. The problem arises when SNR is not good. This work is focused on SNR in the low region, between -20 dB and -5 dB and tried to achieve better results through simulations.

The implementation of ED at -20dB SNR is intended to address the low SNR wall problem that the normal energy detector is experiencing. To overcome low SNR wall problem at worst -20 dB SNR, modification in ED demonstrated by Improved Energy Detector (IED) and Variable Threshold Energy Detector (VTED). ED is implemented for AWGN and Rayleigh channel for SISO and MIMO environments in both CSS and without CSS scenario. When PU's information available, MD is implemented under the same scenario used for ED like with and without CSS environments under heterogenous environments.

Further Rayleigh fading channel environment is used to investigate the Hybrid Detector spectrum sensing technology. In heterogeneous networks, many factors including Probability of Detection ($P_D$), Probability of False Alarm ($P_{FA}$), and SNRs are examined. Results from simulations of without cooperative and Cooperative Spectrum Sensing (CSS) for HD are contrasted. The outcomes demonstrate that HD performs better in terms of $P_D$ and $P_{FA}$ under the CSS scenario. Additionally, it claims that employing CSS, OR logic has improved detector performance. The hybrid detector employs ED and MD spectrum sensing methods. For cognitive radio networks, HD chooses Energy Detector (ED) spectrum detection when knowledge about the PU signal is not available. When it comes to HD outcomes based on information availability from PU, MD excels. HD makes it simple to meet user requests such as a selection of detector, complexity, SNRs, and cooperative spectrum sensing decisions. For the IEEE 802.22 WRAN standard, HD can produce the greatest results in terms of identifying spectrum gaps.

- At -20dB SNR , ED is implemented without and with CSS environments and probability of detection is achieved 0.7 to 1 respectively under heterogeneous environments. This is 0.3 higher compare to previous literature survey results [18].
- Probability of detection is achieved 1 along with probability of false alarm 0 using MD spectrum sensing detector.
- Hybrid detector is implemented using ED and MD as per selection of random variable Z. The best received $P_D$ to 1 and $P_{FA}$ to 0 , which is 0.08 higher than [43] along with 4 CR users and also 0.03 higher than 15 CR users in [45].

More detectors, such as Cyclostationary Feature Detector (CFD) may be added to the hybrid detector in the future for usage when just a portion of the PU signal is known. On USRP radio, a simulation model can be evaluated to sense real-time data. For the developed model for the 802.22 WRAN standard, throughput analysis can also be done.

# CHAPTER 7
# FUTURE SCOPE

In future, more detectors like Cyclostationary feature detectors can also be added to the hybrid detector to use when partial information of PU's signal is available. Simulation model can be tested on USRP radio to sense the real time data. Throughput analysis also can be carried out for developed model for 802.22 WRAN standard.

# CHAPTER 8
# PUBLICATIONS

**Journal Paper (Scopus indexed)**

[1] K. Bani and V. Kulkarni, "Hybrid Spectrum Sensing Using MD and ED for Cognitive Radio Networks," *Journal of Sensor and Actuator Networks*, vol. 11, no. 3, p. 36, Jul. 2022, doi: 10.3390/jsan11030036.

[2] Bani Kavita, Kulkarni Vaishali, "Cooperative Spectrum Sensing under SISO and MIMO Environment for Cognitive Radio Networks", *International Journal of Sensors, Wireless Communications and Control*, vol. 12, issue 4, pp. 302-311, 2022, doi :10.2174/2210327912666220325155817.

**Conference Paper (Scopus indexed)**

[1] Bani, Kavita & Kulkarni, Vaishali, "Analysis of energy detector with improved ED and variable threshold ED suitable for digital TV IEEE 802.22 WRAN", *J. Phys.: Conf. Ser.,* vol. 1706, 012061, 2020, doi :10.1088/1742-6596/1706/1/012061.

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# CHAPTER 9
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